

We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,800

Open access books available

122,000

International authors and editors

135M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Quantifying and Optimizing Failure Tolerance of a Class of Parallel Manipulators

Chinmay S. Ukidve, John E. McInroy and Farhad Jafari
*University of Wyoming, Laramie,
 USA*

1. Introduction

For any robotic system, fault tolerance is a desirable property. This work uses a comparative approach to investigate fault tolerance and the associated problem of reduced manipulability of robots. An important result in combinatorial matrix theory is first obtained. Its consequent modifications are then applied to the theory of fault tolerance of robotic manipulators.

It is shown that for a certain class of parallel manipulators, the mean squared relative manipulability over all possible cases of a given number of actuator failures is always constant irrespective of the geometry of the manipulator. A theorem formulates the value of the mean squared relative manipulability. It is shown that this value depends only upon the number of simultaneous joint failures, the nominal number of joint degrees of freedom and the nominal task degrees of freedom. It is difficult to predict specific failures at the design stage and as such failure of any actuator is considered equally likely. In this context, optimal fault tolerant manipulability is quantified. The theory is applied to a special class of parallel manipulators called Orthogonal Gough-Stewart Platforms (Orthogonal GSPs or OGSPs). A class of two-group symmetric OGSPs which inherently provide for optimal fault tolerant manipulability under a single failure is developed.

2. Background

Robotic manipulators have become popular in numerous applications. They have been employed in automation of industrial processes, underwater exploration, space exploration and innovative defence technologies. The nature of some of these applications makes human presence near manipulators difficult and in many cases, impossible. This is especially true for robots employed in remote and hazardous environments. The repair and maintenance tasks for such robots are extremely difficult. In such cases, operational reliability is of prime importance. Therefore, it is imperative to incorporate failure tolerance in system design. Under the occurrence of failures, fault tolerance enables the robotic system to maintain critical functioning with a reduced level of performance.

Current research efforts are focussed on developing techniques for designing fault tolerant manipulators and robotic vision systems.

Redundant manipulators are rapidly becoming a focus of research due to a multitude of potential advantages they provide. In serial robots, kinematic redundancy has been

Source: Parallel Manipulators, Towards New Applications, Book edited by: Huapeng Wu, ISBN 978-3-902613-40-0, pp. 506, April 2008, I-Tech Education and Publishing, Vienna, Austria

employed for obstacle avoidance (Baillieul, 1990), dexterity optimization (Lewis & Maciejewski, 1992) and torque minimization (Hollerbach & Suh, 1987). In parallel manipulators, singularity avoidance (Kim et al., 2004) and stiffness improvement (Kock & Schumacher, 1998) are broad areas where kinematic redundancy has proven useful. Another significant attribute of redundancy that has come under recent investigation is fault tolerance.

Kinematic failures commonly occur in manipulators. The effect of such failures on manipulator performance depends upon the nature of failure and the nominal kinematic design of the manipulator. For instance, loss of an actuator can render a serial manipulator completely unmanipulable. On the other hand, parallel manipulators can be designed to retain kinematic stability under loss of actuators. Locking of actuators is another commonly observed failure phenomenon. In any failure scenario a robotic system loses partial or complete manipulability. Fault tolerance and the consequent problem of reduced manipulability have been studied by a number of researchers.

Maciejewski (Maciejewski, 1990) associates the concept of fault tolerance to manipulator configuration. Dexterity index is used as a measure of fault tolerance. Optimal fault tolerant configurations are defined using this measure.

Roberts and Maciejewski (Roberts & Maciejewski, 1996) propose a local measure to quantify fault tolerance of a manipulator pose in terms of a manipulability index. Their approach uses the singular value decomposition of the manipulator Jacobian matrix. They describe a direct relation between relative manipulability and the null-space of the Jacobian matrix. They propose relative manipulability index as a measure of fault tolerance.

Paredis, Au and Khosla (Paredis, Au & Khosla, 1994) consider fault tolerance with respect to manipulator workspace and reach. They define fault tolerant workspace of a manipulator and suggest task based design of manipulators. Their approach uses iterative techniques to design manipulators.

Ting, Tosunoglu and Tesar (Ting, Tosunoglu & Tesar, 1993) explore control algorithms for fault tolerant operation of manipulators.

McInroy, O'Brien and Neat (McInroy, O'Brien & Neat, 1999) propose a fault tolerant precision pointing strategy using a class of parallel manipulators called Gough-Stewart Platforms (GSPs) (Stewart, 1966). A GSP is used as a pointing platform to reject vibrations from a noisy spacecraft bus over all frequencies. At low frequencies two-axis or three-axis pointing method is used, while at high frequencies six-axis vibration isolation is employed. The benefits of this approach include broadband pointing stability without a high-bandwidth pointing sensor or destabilizing excitation of the high frequency structural modes. To incorporate fault tolerance, they propose a reconfiguration algorithm to compute a decoupling matrix which allows motion in 'off degrees of freedom' to compensate for failures.

This work uses a comparative approach to investigate fault tolerance and the associated problem of reduced manipulability. Following is a description of the main contributions.

An important result in combinatorial matrix theory is first obtained. Its consequent modifications are then applied to the theory of fault tolerance of robotic manipulators.

It is shown that for a certain class of parallel manipulators, the mean squared relative manipulability over all possible cases of a given number of actuator failures is always constant irrespective of the geometry of the manipulators. This work uses the

manipulability index suggested by Yoshikawa (Yoshikawa, 1985) and the resulting relative manipulability indices proposed by Roberts and Maciejewski (Roberts & Maciejewski, 1996). A theorem formulates the value of the mean squared relative manipulability. It is shown that this constant depends only upon the number of simultaneous failures, the nominal number of joint degrees of freedom and the nominal task degrees of freedom.

It is difficult to predict specific failures at the design stage and as such failure of any actuator is considered equally likely. From this perspective optimal fault tolerant manipulability for a given number of faults has been defined by Roberts and Maciejewski in (Roberts & Maciejewski, 1996). This work quantifies optimal fault tolerant manipulability based only upon the number of simultaneous failures, the nominal number of joint degrees of freedom and the nominal task degrees of freedom.

For parallel manipulators employed in micromanipulation, the workspace is very small. For such manipulators, the definition of optimal fault tolerant manipulability for a given number of faults carries a different interpretation. Such manipulators can be assumed to operate only at a particular pose and therefore the the same definition can be applied to the manipulator in general rather than to a specific pose. As an illustration, the concept of optimal fault tolerant manipulability is applied to a special class of parallel manipulators called Orthogonal Gough-Stewart Platforms (Orthogonal GSPs or OGSPs). This work develops a class of two-group symmetric OGSPs (McInroy & Jafari, 2006) which inherently provide for optimal fault tolerant manipulability under a single failure.

3. Quantifying optimal fault tolerant manipulability

3.1 Manipulability index

In the robotics standard, the Jacobian matrix mapping joint velocities, $\dot{\theta}$, to generalized end effector velocities, V , is denoted by J .

$$V = J\dot{\theta}. \quad (1)$$

A number of researchers have proposed different measures that quantify the manipulability of a manipulator. One such manipulability index, based on a matrix determinant, was proposed by Yoshikawa (Yoshikawa, 1985):

$$w(J) = \sqrt{\det(JJ^T)}. \quad (2)$$

Failures in manipulators can occur in various ways. In this work, only mechanical failures that cause a manipulator to lose an actuator are considered. The impact of such failures varies with different classes of parallel manipulators. In a wide class of parallel mechanisms, under a joint failure, the resulting manipulator Jacobian matrix, referred to as reduced Jacobian matrix, is given by the original Jacobian matrix except that the column corresponding to the failed joint is removed. Gough Stewart Platforms are a classic example of manipulators belonging to this class. On the contrary, in multi-fingered grasps, the impact of failures on the kinematic representation is a function of composite manipulability Jacobian matrix, described in (Wen & Wilfinger, 1999) and cannot be directly derived by elimination of rows or columns.

The mechanisms treated in this work belong to the former class, which will be characterized by $J \in \Omega$. Consider a nominal Jacobian matrix, J , with n actuators. A reduced Jacobian

matrix with i simultaneous actuator failures will be denoted by ${}_iJ$. Note that this ${}_iJ$ is not unique since there may be multiple ways in which i struts may fail. In order to identify all reduced Jacobian matrices uniquely, a subscript j will be used. Therefore, ${}_iJ_j$, $j \in \{1, 2, \dots, {}^nC_i\}$, will describe the alternative i strut failure schemes. This representation will be more clear from the following example.

Suppose J denotes a manipulator with 3 actuators. Then ${}_iJ$ denotes a reduced Jacobian matrix with 1 actuator failure. There are 3C_1 ways in which 1 actuator can fail at a time from 3 actuators. Here, fC_g denotes the usual combinatorial notation. Therefore, ${}_iJ_j$ with $j \in \{1, 2, 3\}$ completely represents all reduced Jacobian matrices.

To analyze the post fault performance of a manipulator the relative manipulability index, ${}_ir_j$, will be used:

$${}_ir_j = \sqrt{\frac{\det({}_iJ_j J_j^T)}{\det(JJ^T)}}. \quad (3)$$

Clearly this index is normalized and the scaled translational and rotational components of the manipulator Jacobian matrix do not affect this value.

3.2 Optimal fault tolerant manipulability

For serial manipulators, (Roberts & Maciejewski, 1996) define optimally fault tolerant configurations have been defined as those J in which the relative manipulability index ${}_ir_j$ remains constant over all possible j , for a given i . A rigorous method is provided in (Roberts & Maciejewski, 1996) to calculate ${}_ir_j$ over all j for a given i . However, that does not allow direct determination of optimal ${}_ir_j$ over all j for a given i . The following theorem shows that for a given n and i the sum of squares of ${}_ir_j$ over all j is invariant. Consequently, a formulation is developed that determines optimal ${}_ir_j$ over all j (Ukideve, McInroy & Jafari, 2006).

Theorem 1. Let J be an $m \times n$ ($n > m$) Jacobian matrix representing the operating configuration of any manipulator having n actuators such that $J \in \Omega$. Then the mean squared relative manipulability over all possible failures j given that i ($i \leq (n - m)$) actuators fail at a time is constant and is given by

$$\sum_{j=1}^{{}^nC_i} \frac{{}_ir_j^2}{{}^nC_i} = \frac{1}{{}^nC_i} \sum_{j=1}^{{}^nC_i} \frac{\det({}_iJ_j J_j^T)}{\det(JJ^T)} = \frac{{}^{(n-i)}C_m}{{}^nC_m}. \quad (4)$$

Proof: Note: Following identities in combinatorics are used in the proof.

$${}_fC_g = \frac{f!}{g!(f-g)!}$$

$${}_fC_g = {}_fC_{(f-g)}$$

Case 1: $i = (n - m)$.

Note

$$\sum_{j=1}^n r_j^2 = \sum_{j=1}^n r_j^2 = \sum_{j=1}^n r_j^2 = 1. \quad (5)$$

This equality follows from the Binet-Cauchy Theorem, because for $i = (n - m)$

$$\det(JJ^T) = \sum_{j=1}^n \det(J_{ji} J_j^T). \quad (6)$$

Case 2: $i < (n - m)$.

Let $c_k \in \mathbb{R}^n$, denote the k^{th} column of J ($k = 1$ to n). Then,

$$J = \begin{bmatrix} c_1 & c_2 & \dots & c_n \end{bmatrix},$$

and

$$JJ^T = c_1 c_1^T + c_2 c_2^T + \dots + c_n c_n^T. \quad (7)$$

Let $(n - m) = t$.

By Binet-Cauchy Theorem,

$$\det(JJ^T) = \sum_{j=1}^n \det(J_{ji} J_j^T). \quad (8)$$

Suppose i actuators fail at a time from n actuators ($i < t$). This leads to a reduced Jacobian matrix J_j with $j \in \{1, 2, \dots, {}^n C_i\}$. Without loss of generality, we may assume that the actuators corresponding to last i columns fail. This says that all the reduced Jacobian matrices can be completely expressed by J_j with $j \in \{1, 2, \dots, {}^{n-i} C_m\}$. Note that although this loss of generality argument is not applicable to the reduced Jacobian matrix, equation (7) makes it clear that the argument is valid for the product of the reduced Jacobian matrix and its transpose. The number of actuators remaining is $(n - i)$. The number of ways in which the failures can happen at a time are ${}^n C_i$. In other words, ${}^n C_i = {}^n C_{(n-i)}$ is the number of ways in which $(n - i)$ un-failed actuators can be chosen from n actuators. So, there will be ${}^n C_i$ such reduced Jacobian matrices, J_j , where $j \in \{1, 2, \dots, {}^n C_i\}$.

Apply the Binet-Cauchy Theorem to a representative reduced Jacobian matrix J_j , denoted by J_j^1 .

Then, we have

$$\det(J_j^1 J_j^{1T}) = \sum_{j=1}^{(n-i)} \det(J_{ji}^1 J_j^{1T}). \quad (9)$$

Similarly,

$$\det({}_i J_{ji}^2 J_j^{2T}) = \sum_{j=1}^{(n-i)C_m} \det({}_i J_{ji}^2 J_j^{2T}). \quad (10)$$

In general,

$$\det({}_i J_j^n C_i J_j^n C_i^T) = \sum_{j=1}^{(n-i)C_m} \det({}_i J_j^n C_i J_j^n C_i^T). \quad (11)$$

Note that all of the ${}^{(n-i)}C_m$ terms appearing on the R.H.S. of equation (9) are exactly those terms on the R.H.S. of equation (8) which do not have the eliminated i columns in their submatrices ${}_i J_j$. Moreover, each equation from ((9) - (11)) has one term on the L.H.S and ${}^{(n-i)}C_m$ terms on the R.H.S and there are ${}^m C_i$ such equations.

Using equations ((9) - (11)) to add all possible ${}^m C_i$ reduced Jacobian matrices ${}_i J_j^1, {}_i J_j^2, \dots, {}_i J_j^n C_i$ i.e. taking the summation of all possible ${}^m C_i$ reduced Jacobian matrices,

$$\begin{aligned} & \det({}_i J_{ji}^1 J_j^{1T}) + \det({}_i J_{ji}^2 J_j^{2T}) + \dots + \det({}_i J_j^n C_i J_j^n C_i^T) \\ &= \sum_{j=1}^{(n-i)C_m} \det({}_i J_{ji}^1 J_j^{1T}) + \sum_{j=1}^{(n-i)C_m} \det({}_i J_{ji}^2 J_j^{2T}) + \dots \\ & \dots + \sum_{j=1}^{(n-i)C_m} \det({}_i J_j^n C_i J_j^n C_i^T). \end{aligned} \quad (12)$$

Now comparing equation (8) with equation (12), each term in the R.H.S. of (12) is a term on the R.H.S. of (8). Choose a particular term on the R.H.S. of (8), for example $\det({}_i J_i J_i^T)$. This term will occur in only those $\det({}_i J_{ji}^p J_j^{pT})$ ($p=1$ to ${}^m C_i$) for which ${}_i J_j^p$ contains exactly those n columns in ${}_i J_i$. For n given columns, the number of columns left to choose for ${}_i J_j$; with i columns eliminated is $(n-m)$; from which we choose the remaining $(n-m-i)$ columns. Therefore, the number of occurrences for $\det({}_i J_i J_i^T)$ will be ${}^{(n-m)}C_{(n-m-i)}$.

This is true for each term on the R.H.S. of (8). Furthermore, we also know that each term from the ${}^{(n-i)}C_m$ terms appearing on the R.H.S. of ${}^m C_i$ equations ((9) - (11)) occurs in the R.H.S. of equation (8).

Dividing equation (12) by (8), we have

$$\frac{\det({}_i J_{ji}^1 J_j^{1T})}{\det(JJ^T)} + \frac{\det({}_i J_{ji}^2 J_j^{2T})}{\det(JJ^T)} + \dots + \frac{\det({}_i J_j^n C_i J_j^n C_i^T)}{\det(JJ^T)} = {}^{(n-m)}C_{(n-m-i)}. \quad (13)$$

Therefore,

$$\sum_{j=1}^n r_j^2 = \sum_{j=1}^n \frac{\det({}_i J_{ji} J_j^T)}{\det(JJ^T)} = {}^{(n-m)}C_{(n-m-i)}. \quad (14)$$

Dividing both sides by ${}^m C_i$ to take the mean and noting that,

$${}^{(n-m)}C_{(n-m-i)} = \frac{{}^{(n-i)}C_m^n}{{}^nC_m} C_i, \quad (15)$$

the result follows.

#

This proof leads to the definition of optimal fault tolerant manipulability.

Definition: A manipulator operating about a single point in the workspace is said to be optimally fault tolerant for a given number of failures i if for all $j \in \{1, 2, \dots, {}^nC\}$

$${}_i r_j = c \quad (16)$$

where c is a constant.

It is clear from Theorem 1 that if post-fault relative manipulability for certain cases of failure are higher than the optimal fault tolerant manipulability value, then for other worst cases of failure, post-fault relative manipulabilities are extremely low. This has precisely been the motivation for developing optimally fault tolerant manipulators and the above definition arises as a direct consequence.

Corollary 2. A manipulator characterized by $J \in \Omega$ and operating about a single point in the workspace is optimally fault tolerant to i faults if

$${}_i r_j = \sqrt{\frac{{}^{(n-i)}C_m^n}{{}^nC_m}} \quad (17)$$

for all $j \in \{1, 2, \dots, {}^nC\}$.

Proof: Equation (16) defines manipulators with optimal fault tolerant manipulability for i faults. By Theorem 1, if each ${}_i r_j$ is constant, c is given by equation (1)

#

Roberts and Maciejewski (Roberts & Maciejewski, 1996) present a singular value decomposition approach to identify fault tolerant configurations for serial manipulators and describes a rigorous method to determine whether a given nominal configuration possesses optimal fault tolerant manipulability. The above theorem states a formulation which directly gives the value of optimal manipulability under a given number of failures, for any manipulator with a given number of actuators. In fact, the theorem proves that irrespective of the operating configuration, all manipulators having the same number of actuators, have the same value of optimal manipulability under a given number of failures. This new idea plays a key role in the design of fault tolerant serial manipulators. The following example illustrates this point.

Suppose a fault tolerant serial manipulator is to be designed such that it has 3 degrees of freedom ($m = 3$) and it is desired to have an optimal fault tolerant manipulability of 0.5 ($r_j = 0.5$) under a single-actuator failure ($i = 1$). This implies that the manipulator operating in the nominal configuration, should be able to sustain the failure of any actuator and retain half of its manipulability. Substituting all known values in equation (1), we get $n = 4$. This means that the manipulator has to have 4 actuators in order to have optimal fault tolerant manipulability for single failure.

Another implication of this theorem is significant in terms of understanding post-fault behavior of any manipulator. From equation (14), it is clear that if the value of r_j is quite close to $^{(n-m)}C_{(n-m-i)}$ for some j then the reduction in manipulability is far more pronounced if a possible failure combination corresponding to some other j were to occur. Taking this into account, it is possible to assemble the actuators in such a way that actuators which are more likely to fail (for example, actuators with actuators that are more likely to have manufacturing defects) correspond to those j which give

$$r_j > \sqrt{\frac{^{(n-i)}C_m}{^nC_m}}.$$

This idea has a greater impact on the design of parallel manipulators. While actuator failures may cause a serial manipulator to stop functioning, actuator failures have a comparatively smaller effect on redundant parallel manipulators because they can retain kinematic stability. Therefore, the two consequences that can be applied to the design of serial manipulators are applicable to parallel manipulators as well.

The most significant area of investigation where the above results influence parallel manipulator design is the choice of geometry. This area will be explored in the Section 5.

3.3 Examples

Some specific examples provide more insight to understanding this concept of optimal fault tolerant manipulability.

Number of Nominal Actuators n	Number of Failures i	Sum of all possible r_j^2	Optimal Fault Tolerant Manipulability
7	1	1	0.377
8	1	2	0.500
8	2	2	0.189
9	1	3	0.577
9	2	3	0.288
9	3	3	0.109

Table 1. Optimal Fault-tolerant manipulability of 6-dof redundant manipulators

It is clear from Table 1 that as the number of failures increases, the optimal fault tolerant manipulability decreases drastically, regardless of the geometry. Consider the example of any 8-actuator manipulator suffering from 2 simultaneous failures. The sum of squares of relative manipulabilities is 2 for 28 failure possibilities. This means that if some post-fault relative manipulabilities are more than the optimal fault tolerant manipulability (0.189), then the worst case values are far less than 0.189. Therefore, irrespective of the geometry of the 8-actuator manipulator, for worst cases of failure the relative manipulabilities will have negligible values. Hence, it is important to design manipulators that are optimally fault tolerant to a given number of failures.

Table 1 also provides another important inference which is significant from the design perspective. Any redundant manipulator gives very low optimal fault tolerant manipulability values for more than one failures, and these values decrease drastically with number of failures. For example, for two failures in an octopod the optimal fault tolerant manipulability is 0.189 and, for two and three failures in a nanopod the optimal fault tolerant manipulabilities are 0.288 and 0.109 respectively. This means that under the hypothesis of equal probability of failure for each actuator, it is not practical to design manipulators optimally fault tolerant to more than one fault.

4. Symmetric orthogonal Gough Stewart platforms

4.1 Gough Stewart platforms

A Gough-Stewart Platform (GSP) is a parallel manipulator consisting of a base, a moving platform (or payload) and struts. The length of struts is controlled by actuators. The struts have spherical joints at the payload end and U joints at the base. To provide six degrees of freedom, six struts are commonly used. Figure 1 is a diagrammatic representation of a GSP. Payload attachment points and base attachment points are represented by p_i and q_i ($i \in \{1,2,3,4,5,6\}$) respectively.

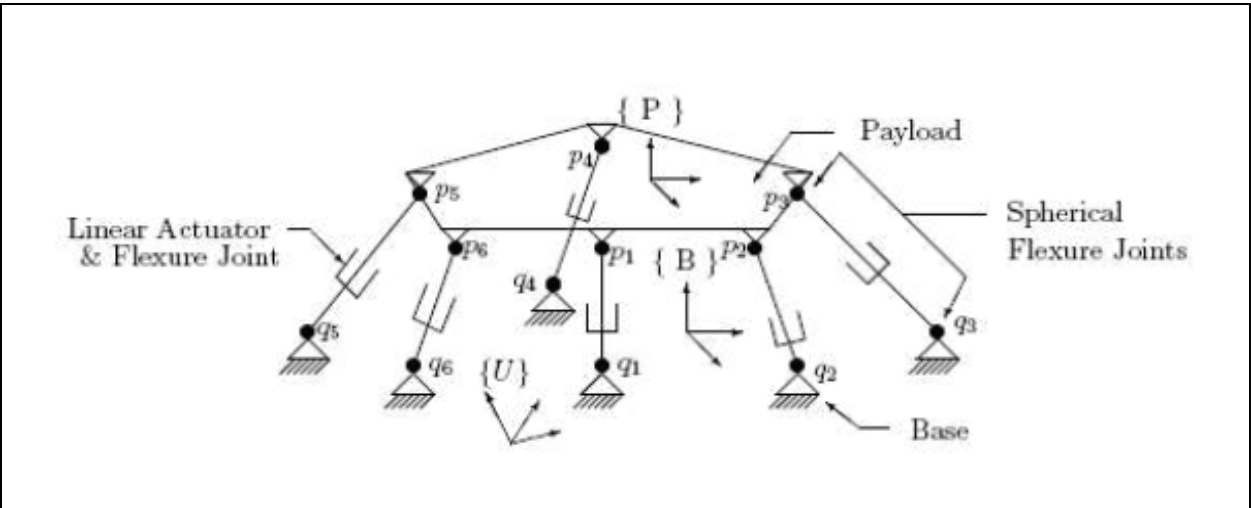


Fig. 1. Gough-Stewart Platform

OGSPs are a special class of GSPs that provide kinematic and dynamic decoupled control. Therefore, OGSPs are being widely used in commercial, military and space applications. Scientists at Northrop Grumman Space Technologies (NGST) are currently experimenting with an 8-strut OGSP. More recent applications of OGSPs include laser tracking and pointing, ultra-precise manipulation (McInroy & Jafari, 2006) and robotic surgery (Wapler et al., 2003). The very nature of these applications makes maintenance or repair of manipulators very difficult. Moreover, a single failure may compromise the fulfilment of objective or cause costly downtime. As a consequence, it is desirable to design OGSPs which can sustain failures, while retaining an acceptable level of manipulability. Figure 2 shows one of the flexure jointed hexapods at the University of Wyoming. It has a mutually orthogonal geometry.

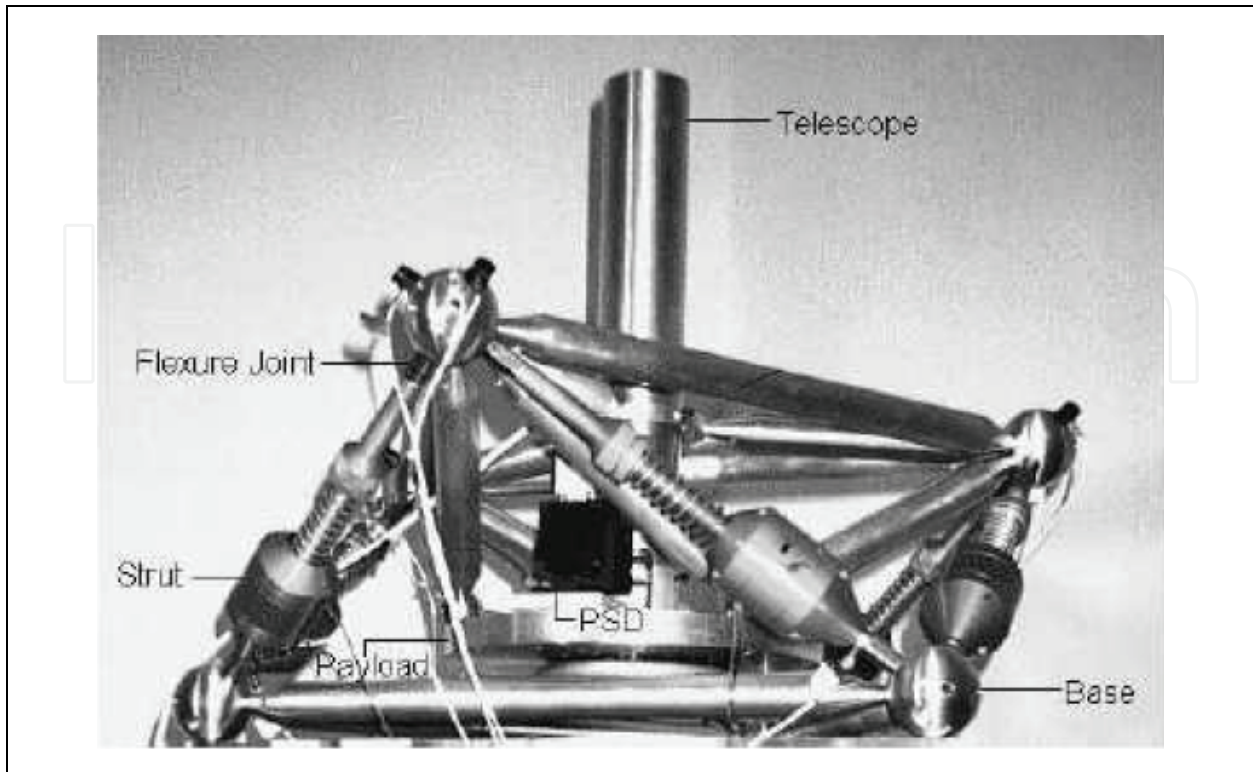


Fig. 2. A Flexure Jointed Hexapod at the University of Wyoming

Recent research has shown that symmetric groups of struts can be used to generate OGSPs having desired properties at their home position (McInroy & Jafari, 2006) and several new results have been obtained.

The following part of this section recapitulates important results from (McInroy & Jafari, 2006).

4.2 Kinematics of symmetric OGSPs

The inverse Jacobian, M , of a GSP maps the generalized velocity of the payload to the corresponding joint velocities of each strut ($\dot{\theta} = MV$). It has the form:

$$M = \begin{bmatrix} \vec{u}_1^T & \vec{v}_1^T \\ \vdots & \vdots \\ \vec{u}_l^T & \vec{v}_l^T \end{bmatrix} \quad (18)$$

where $\vec{u}_i, \vec{v}_i \in \mathbb{R}^3$, $\vec{v}_i = \vec{p}_i \times \vec{u}_i$, \vec{u}_i is the unit vector along strut i and $\vec{p}_i \in \mathbb{R}^3$ is the moving platform attachment point of strut i . Please refer to Figure 1. Note that, even though M is called the inverse Jacobian to comply with the robotics standard, its computation does not require inversion, thus it is well defined for all GSP.

Definitions: Let $M \in M_{l \times 6}(\mathbb{R})$. Write

$$M = \begin{bmatrix} U^T & V^T \end{bmatrix}$$

where $U, V \in M_{3 \times l}(\mathbb{R})$. We say $M \in \text{GSP}$, M is a Gough-Stewart Platform, if:

- $\text{diag}(U^T U) = [1 \ 1 \ \dots \ 1]$
- $\text{diag}(U^T V) = 0$

We say M is a Weighted Orthogonal Gough-Stewart Platform, $M \in \text{w-OGSP}$, if $M \in \text{GSP}$ and:

- $M^T K M$ is a diagonal matrix for a diagonal K .

Where $K = I$ these matrices become the Orthogonal Gough-Stewart Platforms.

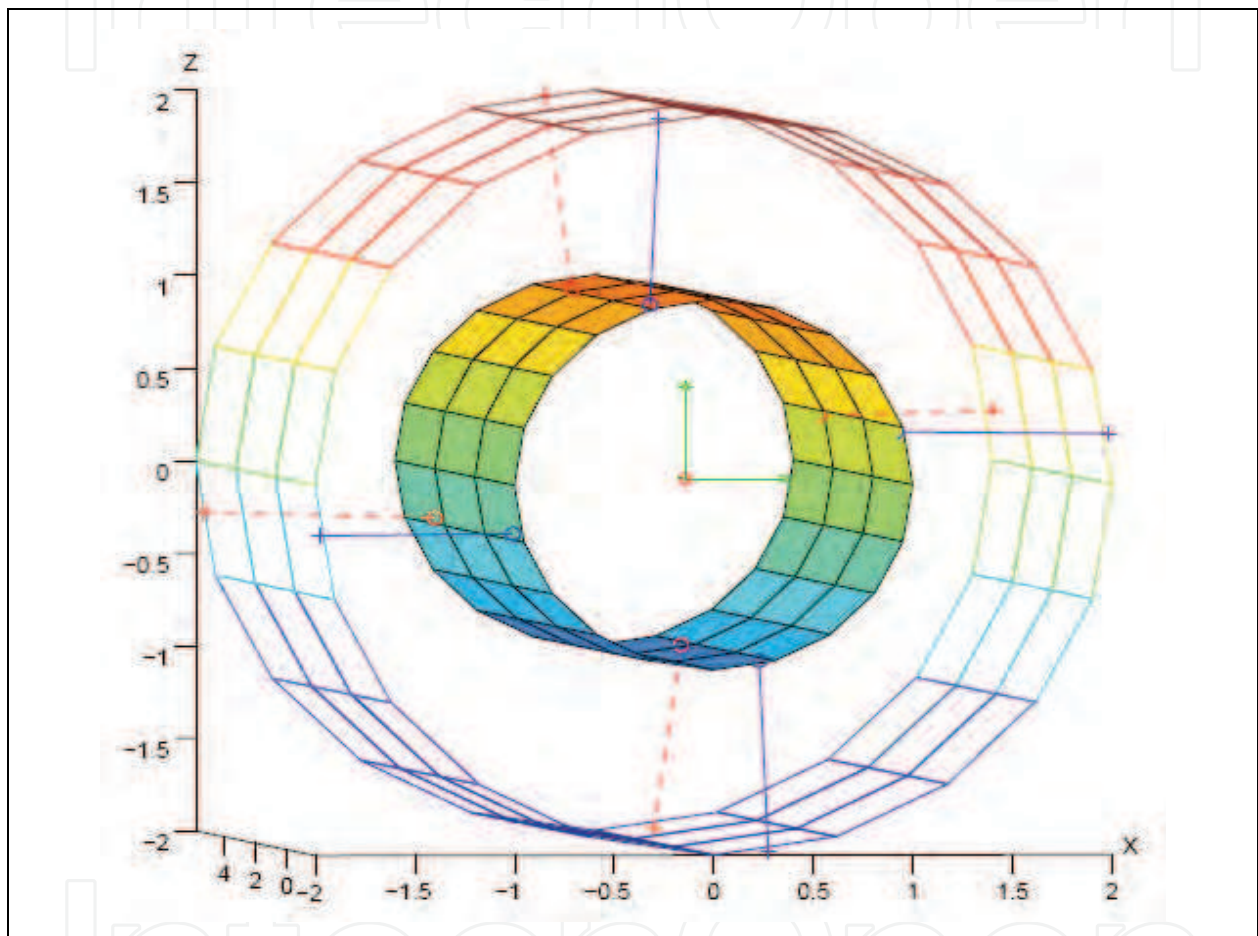


Fig. 3. [4 4] cylindrical OGSP with optimal fault tolerant manipulability

(McInroy & Jafari, 2006) develops properties and designs of symmetrical weighted OGSPs. Struts that are geometrically symmetrical are treated together, so the entire OGSP is decomposed into m different groups, with the i^{th} group having n_i struts. Then

$$\vec{n} = [n_1 \quad n_2 \quad \dots \quad n_m]^T$$

is a vector of positive integers describing the number of struts in each group. The total number of struts in the GSP is then $l = \sum_{j=1}^m n_j$. Let $\vec{u}_j, \vec{v}_j \in \mathbb{R}^3$ correspond to the i^{th} strut in group j . Let $U = [\vec{u}_{11} \ \vec{u}_{12} \ \dots \ \vec{u}_{1n_1} \ \vec{u}_{21} \ \vec{u}_{22} \ \dots \ \vec{u}_{2n_2} \ \dots \ \vec{u}_{m1} \ \vec{u}_{m2} \ \dots \ \vec{u}_{mn_m}]$ and $V = [\vec{v}_{11} \ \vec{v}_{12} \ \dots \ \vec{v}_{1n_1} \ \vec{v}_{21} \ \vec{v}_{22} \ \dots \ \vec{v}_{2n_2} \ \dots \ \vec{v}_{m1} \ \vec{v}_{m2} \ \dots \ \vec{v}_{mn_m}]$. A GSP can then be found for these struts by letting $M = [U^T \quad V^T]$.

Following is the summary of results in (McInroy & Jafari, 2006).

Proposition 3. Conditions (a) and (b) in the GSP definition are satisfied if

$$\vec{u}_{ij} = \begin{bmatrix} S_{\phi_{ij}} C_{\beta_{ij}} \\ S_{\phi_{ij}} S_{\beta_{ij}} \\ C_{\phi_{ij}} \end{bmatrix}, \vec{v}_{ij} = x_{ij} \vec{v}_{x_{ij}} + y_{ij} \vec{v}_{y_{ij}} \quad (19)$$

where $S_x = \sin x$, $C_x = \cos x$, $\phi_{ij}, \beta_{ij}, x_{ij}, y_{ij} \in \mathbb{R}$, and

$$\vec{v}_{x_{ij}} = \begin{bmatrix} S_{\beta_{ij}} \\ -C_{\beta_{ij}} \\ 0 \end{bmatrix}, \vec{v}_{y_{ij}} = \begin{bmatrix} C_{\phi_{ij}} C_{\beta_{ij}} \\ C_{\phi_{ij}} S_{\beta_{ij}} \\ -S_{\phi_{ij}} \end{bmatrix}. \quad (20)$$

Conversely, if $M \in \text{GSP}$, then M may be represented by a parameterization given by (19) and (20).

Theorem 4. Let all groups contain more than two struts, i.e. $\min n_j > 2$. Then $M \in \text{w-OGSP}$ if

- The same angle, ϕ_j , is used for all struts in group j , i.e. $\phi_{ij} = \phi_j$,
- The same x component of \vec{v} , x_j , is used for all struts in group j , i.e. $x_{ij} = x_j$,
- The same y component of \vec{v} , y_j , is used for all struts in group j , i.e. $y_{ij} = y_j$,
- The same k , k_j , is used for all struts in group j , i.e. $k_{ij} = k_j$,
- Struts in a group are rotated about the z-axis equal amounts, i.e. $\beta_{ij} = \beta_j + \frac{2\pi(i-1)}{n_j}$,
- $A_x \vec{x} = 0$ and $A_y \vec{y} = 0$,

where

$$\vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix}, \vec{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}, \vec{\phi} = \begin{bmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_m \end{bmatrix},$$

$$\vec{k} = \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_m \end{bmatrix}, \vec{\beta} = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_m \end{bmatrix},$$

$$A_x = [k_1 n_1 S_{\phi_1} \ k_2 n_2 S_{\phi_2} \ \cdots \ k_m n_m S_{\phi_m}], \quad (21)$$

$$A_y = [k_1 n_1 S_{2\phi_1} \ k_2 n_2 S_{2\phi_2} \ \cdots \ k_m n_m S_{2\phi_m}]. \quad (22)$$

$\phi_j, \beta_j, k_j \in \mathbb{R}$ may be freely chosen. \bar{x} and $\bar{y} \in \mathbb{R}^n$ may be freely chosen to satisfy (F). Furthermore, if σ_i^2 denotes the i^{th} diagonal element of $M^T KM$, then

$$\sigma_1^2 = \sigma_2^2 = \frac{1}{2} \sum_{j=1}^m n_j k_j S_{\phi_{ij}}^2, \quad (23)$$

$$\sigma_3^2 = \sum_{j=1}^m n_j k_j - 2\sigma_1^2, \quad (24)$$

$$\sigma_4^2 = \sigma_5^2 = \frac{1}{2} \sum_{j=1}^m n_j k_j (x_j^2 + y_j^2 C_{\phi_{ij}}^2), \quad (25)$$

$$\sigma_6^2 = \sum_{j=1}^m n_j k_j y_j^2 S_{\phi_{ij}}^2. \quad (26)$$

In (Aphale, 2006) robust fault tolerance is defined as the property by which the rank of M equals 6 or the number of struts remaining after failures, whichever is minimum. Not all geometric designs of OGSPs are robustly fault tolerant. In fact, it has been proved that [3 3 2] geometry gives the only robustly fault tolerant design for 8- strut (octopod) OGSPs. This means that [3 3 2] geometry is the only one wherein, if any two struts fail, the rank of M remains 6. While robust fault tolerance guarantees motion in 6 degrees of freedom for a n - strut platform under any $n - m$ failures ($m \leq (n - 6)$), experiments made on the University of Wyoming octopod clearly show that robustly fault tolerant designs suffer from serious post-fault stability problems due to poor conditioning. On the other hand, in many cases the design specifications may require a single failure tolerant architecture. For instance, in a typical case, it would be better to design an 8-strut OGSP which gives an optimal fault tolerant manipulability of 0.5 for a single failure, instead of designing a robustly fault tolerant 8-strut OGSP. This argument will be clearer from the example explained in the next section where a class of symmetric OGSPs having optimal fault tolerant manipulability is proposed.

5. Fault tolerant Gough Stewart platforms

5.1 Design

For parallel manipulators, the problem of inverse kinematics is easier to solve. Therefore, in most literature on parallel manipulators, the inverse Jacobian, M , is used for study.

Remark: In this work, it is assumed that the Jacobian relating joint and Cartesian motion is constant. This is equivalent to considering that the operation is about a single point, rather than across a workspace. The rationale for making this assumption is that there are several high precision OGSP applications which demand operation over a very small workspace. These include high precision motion control for telescopes, scanning microscopes, integrated circuit fabrication, stiffness, precision pointing and vibration isolation.

As mentioned in Section 3, [4 4] redundant OGSPs are currently under investigation by a number of researchers. This section develops a more general class of symmetric OGSPs with optimal fault tolerant manipulability under one fault.

A key characteristic of symmetric OGSPs is rotational invariance. Rotational invariance of groups of struts can be clearly understood with the help of Figure 3, Figure 4 and Figure 5. Figure 3 represents a symmetric 8-strut OGSP, having M given as,

$$\begin{bmatrix} 0.8660 & 0.0000 & 0.5000 & 0.1369 & -0.5969 & -0.2372 \\ 0.0000 & 0.8660 & 0.5000 & 0.5969 & 0.1369 & -0.2372 \\ -0.8660 & 0.0000 & 0.5000 & -0.1369 & 0.5969 & -0.2372 \\ 0.0000 & -0.8660 & 0.5000 & -0.5969 & -0.1369 & -0.2372 \\ 0.0000 & 0.5000 & 0.8660 & -1.0338 & -0.2372 & 0.1369 \\ -0.5000 & 0.0000 & 0.8660 & 0.2372 & -1.0338 & 0.1369 \\ 0.0000 & -0.5000 & 0.8660 & 1.0338 & 0.2372 & 0.1369 \\ 0.5000 & 0.0000 & 0.8660 & -0.2372 & 1.0338 & 0.1369 \end{bmatrix}$$

It can be clearly seen that a strut failure in group 1 (Figure 4) or a strut failure in group 2 (Figure 5) causes the same effective change in manipulability.

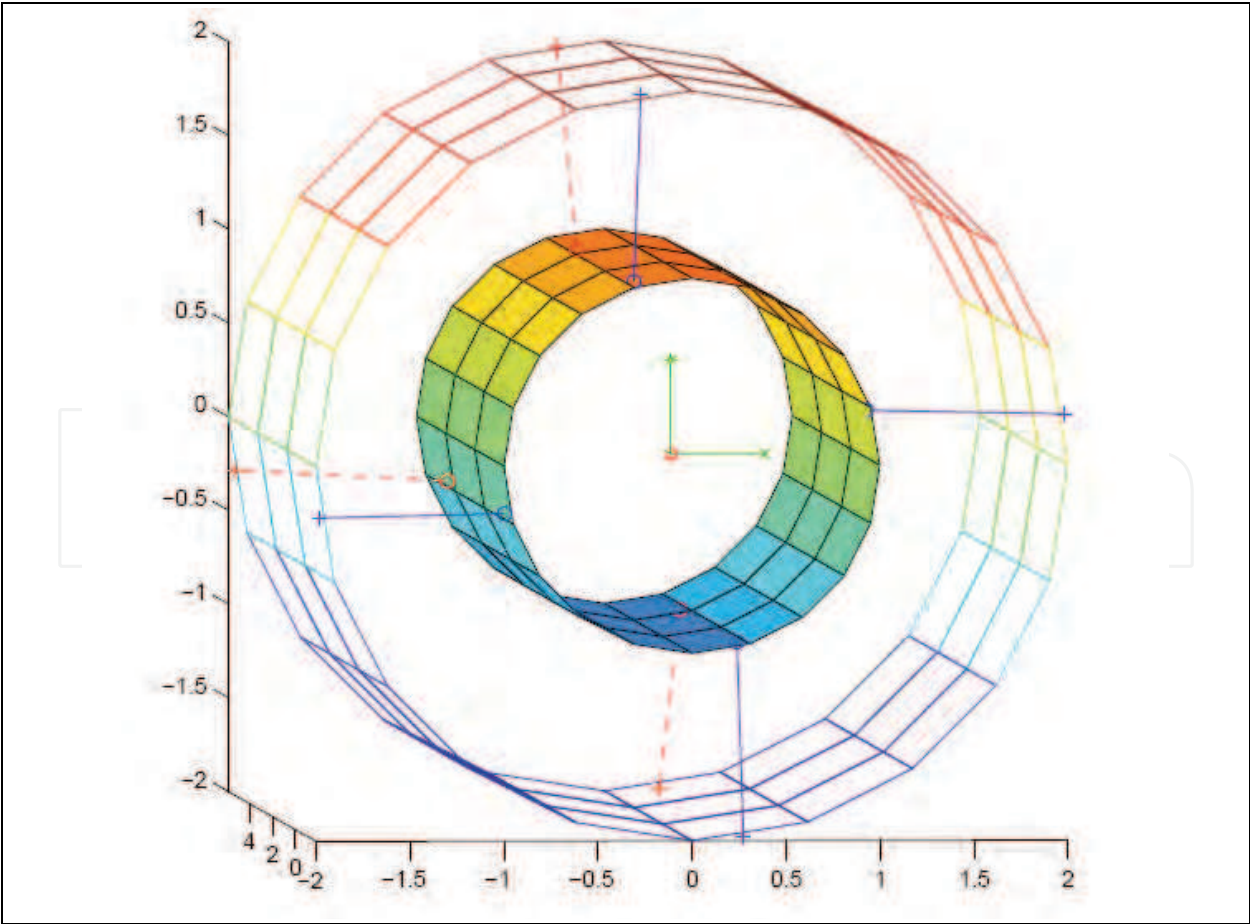


Fig. 4. [4 4] cylindrical OGSP with one failure in group 1.

This prominent feature provides symmetric OGSPs with inherent optimal fault tolerant manipulability under the occurrence of a failure. Furthermore, for symmetric OGSPs it is possible to estimate post-fault reduction in manipulability by knowing the geometry. This is explained in the following theorem.

Theorem 5. For a $[p \ q]$ ($p > 3, q \geq 3$ or $q > 3, p \geq 3$) geometry, satisfying (A)- (F) in Theorem 4, the relative manipulability after a single failure in group $[p]$ is given by r_p where r_p is the optimal fault tolerant manipulability under one fault for an OGSP with $[p \ p]$ geometry. For the remaining cases of failure i.e. those corresponding to group $[q]$, the relative manipulability is given by r_q where r_q is the optimal fault tolerant manipulability under one fault for an OGSP with $[q \ q]$ geometry.

Proof: Consider a manipulator with $[p \ q]$ ($p > 3, q \geq 3$ or $q > 3, p \geq 3$) geometry. Let M_p and M_q denote the inverse Jacobian corresponding to each group. Then the composite inverse Jacobian matrix M is given by

$$M = \begin{bmatrix} M_p \\ M_q \end{bmatrix}. \quad (27)$$

Consider the case that a single link in group $[p]$ fails. Then from rank one perturbation of a matrix, we have

$$\det(M^T M) = \det(M'^T M') (1 + p_f (M'^T M')^{-1} p_f^T) \quad (28)$$

where p_f represents the row of M_p corresponding to the link failure and M' represents the inverse Jacobian matrix after failure. Then,

$$\frac{\det(M'^T M')}{\det(M^T M)} = \frac{1}{(1 + p_f (M'^T M')^{-1} p_f^T)}. \quad (29)$$

Using the Matrix Inversion Lemma for the expression on the R.H.S. of equation (29)

$$\frac{\det(M'^T M')}{\det(M^T M)} = 1 - (p_f (M'^T M' + p_f^T p_f)^{-1} p_f^T). \quad (30)$$

Using the formulation as in equation (7), we have

$$\frac{\det(M'^T M')}{\det(M^T M)} = 1 - (p_f (M^T M)^{-1} p_f^T). \quad (31)$$

Using conditions (A)- (F) given in Theorem 4, for a $[p \ q]$ geometry with equal strut stiffness, we have

$$\varphi_{i1} = \varphi_p, \varphi_{i2} = \varphi_q,$$

$$\begin{aligned}x_{i1} &= x_p, x_{i2} = x_q, \\ y_{i1} &= y_p, y_{i2} = y_q,\end{aligned}\tag{32}$$

and

$$(M^T M)^{-1} = \text{diag}\left[\frac{1}{\sigma_1^2} \frac{1}{\sigma_2^2} \frac{1}{\sigma_3^2} \frac{1}{\sigma_4^2} \frac{1}{\sigma_5^2} \frac{1}{\sigma_6^2}\right].\tag{33}$$

Note that p_f also has a trigonometric parametrization given by Proposition 3.

$$p_f^T = \begin{bmatrix} S_{\varphi_p} C_{\beta_{ij}} \\ S_{\varphi_p} S_{\beta_{ij}} \\ C_{\varphi_p} \\ S_{\beta_{ij}} + C_{\varphi_p} C_{\beta_{ij}} \\ -C_{\beta_{ij}} + C_{\varphi_p} S_{\beta_{ij}} \\ S_{\varphi_p} \end{bmatrix},\tag{34}$$

and substituting equation (32) in equations ((23)-(26)), we get

$$\sigma_1^2 = \sigma_2^2 = \frac{1}{2}(pS_{\varphi_p}^2 + qS_{\varphi_q}^2),\tag{35}$$

$$\sigma_3^2 = (p + q) - 2\sigma_1^2,\tag{36}$$

$$\sigma_4^2 = \sigma_5^2 = \frac{1}{2}(p(x_p^2 + y_p^2 C_{\varphi_p}^2) + q(x_q^2 + y_q^2 C_{\varphi_q}^2)),\tag{37}$$

and

$$\sigma_6^2 = (py_p^2 S_{\varphi_p}^2 + qy_q^2 S_{\varphi_q}^2).\tag{38}$$

Substituting equations ((35)-(38)) into equation(33), we get $(M^T M)^{-1}$ in terms of design parameters. Using this formulation of $(M^T M)^{-1}$ into equation (31), then substituting equation (34) in equation (31) and simplifying the complicated trigonometric expression, we get

$$\frac{\det(M'^T M')}{\det(M^T M)} = 1 - (p_f(M^T M)^{-1} p_f^T) = 1 - \frac{3}{p}.\tag{39}$$

It is important to note that this expression does not depend upon q or the particular geometric parameters ϕ_y , x_y , y_y and β_y .

Note that the optimal fault tolerant manipulability for any [p p] manipulator is given by equation (1) in Theorem 2. Hence,

$${}_1r_j = \sqrt{\frac{{}^{(2p-1)}C_6}{{}^{2p}C_6}} = \sqrt{1-\frac{3}{p}}. \tag{40}$$

Since the choice of p does not cause any loss of generality, we have

$${}_1r'_j = \sqrt{\frac{{}^{(2q-1)}C_6}{{}^{2q}C_6}} = \sqrt{1-\frac{3}{q}}. \tag{41}$$

#

Results from this Theorem are plotted in Figure 6. Figure 6 depicts the change in values of the relative manipulability, for different geometries, under the occurrence of one failure. This Theorem proves the independence of the manipulability contributions of each symmetric group of a two-group OGSPs which may have different number of struts in each group. It is shown that within the group, any failure will give the same manipulability reduction even in any two-group OGSPs. Figure 6 depicts the change in relative manipulability under on failure, for symmetric OGSPs with different two-group geometrical designs.

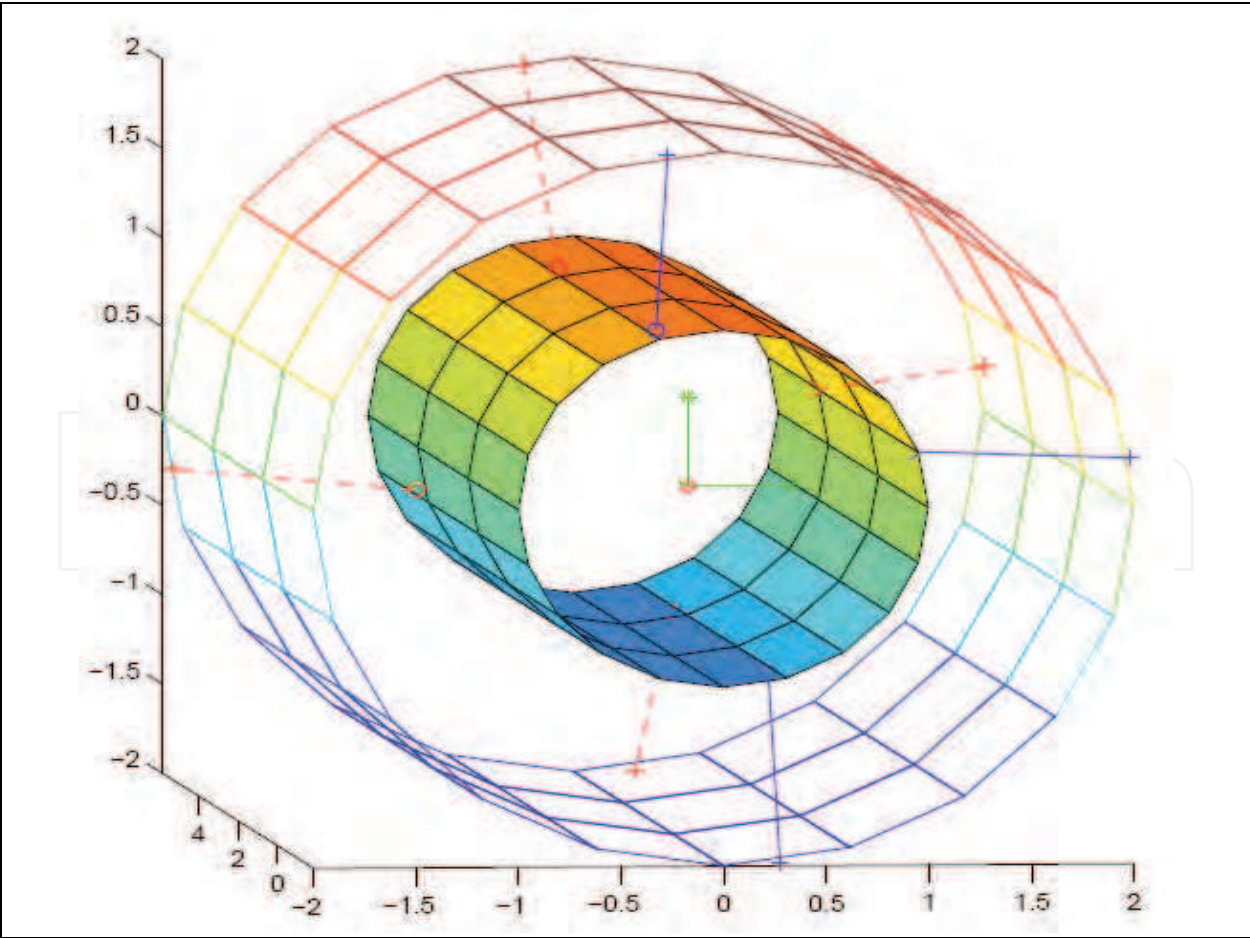


Fig. 5. [4 4] cylindrical OGSP with one failure in group 2.

Looking at Figure 6 it is now possible to estimate the level of post fault reduction in manipulability of symmetric OGSPs. Corollary 6 proves that all two-group OGSPs (i.e. with [m m] (m > 3) geometries) possess optimal fault tolerant manipulability.

Corollary 6. Any 2s-strut OGSP with [s s] (s > 3) geometry generated by Theorem 4 possesses optimal fault tolerant manipulability under one fault and its value is given by,

$${}_1r_j = \sqrt{\frac{{}^{(2s-1)}C_6}{{}^{2s}C_6}} \tag{42}$$

for all $j \in \{1,2,..., {}^{2s}C_1\}$.

Proof: Consider a manipulator with [p q] (p > 3,q ≥ 3 or q > 3,p ≥ 3) geometry. Substitute q = p = s. Using Theorem 5,

$${}_1r_j = \sqrt{\frac{{}^{(2s-1)}C_6}{{}^{2s}C_6}} \tag{43}$$

for all $j \in \{1,2,..., {}^{2s}C_1\}$.

#

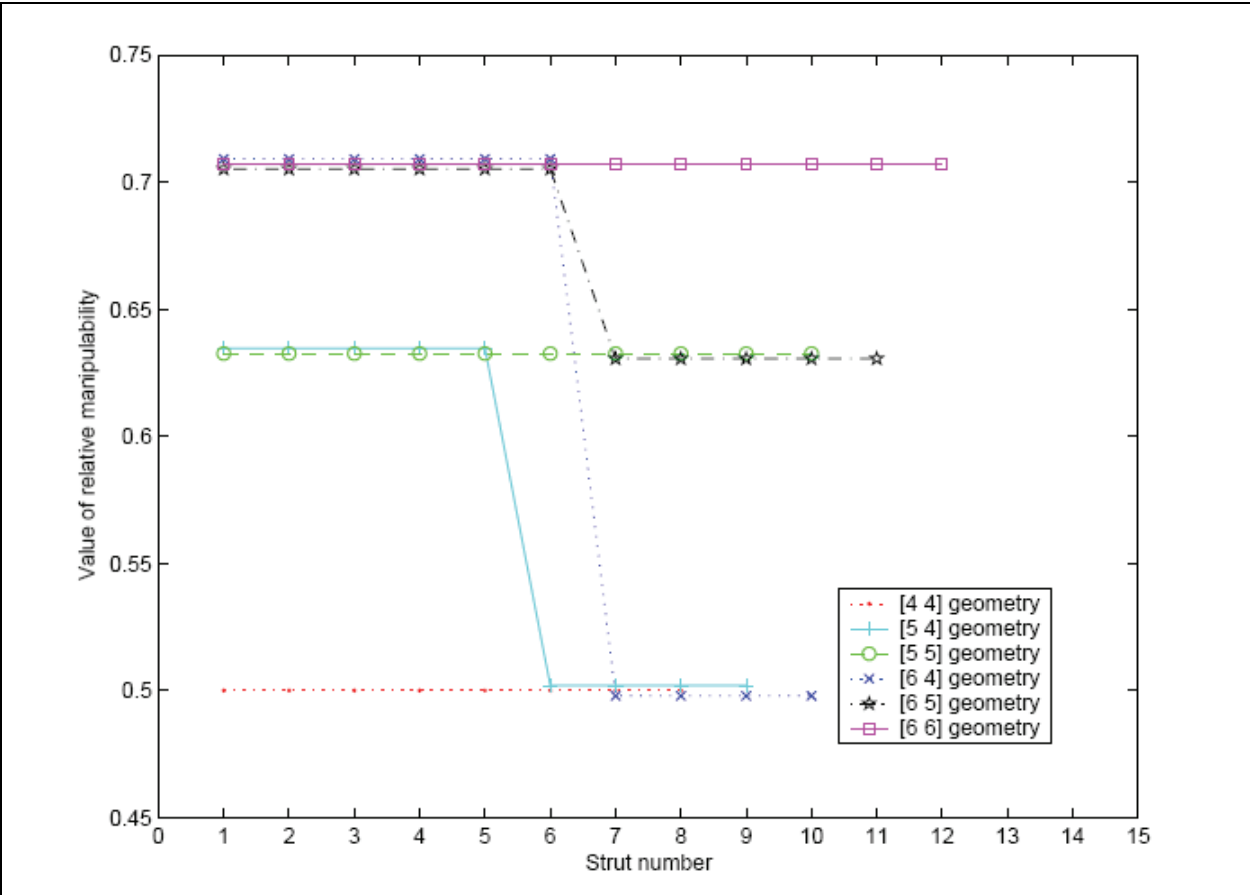


Fig. 6. Variation of the relative manipulability under a single failure, for various two group geometries

For the particular case of a symmetric 8-strut OGSP introduced at the beginning of this section,

$${}_1r_j = 0.5 \text{ for all } j \in \{1, 2, \dots, 8\}.$$

This inherent property possessed by symmetric OGSPs can be put to a significant advantage in design. Theorem 5 and Corollary (6) allow freedom of designing symmetric OGSPs with a high value of nominal manipulability. For example, by Corollary (6) it is seen that an 8-strut OGSP sustains any single-strut failure while retaining half of its nominal manipulability. The optimal fault tolerant manipulability of symmetric OGSPs makes them a suitable choice for critical applications where failure tolerance is necessary.

5.2 Singularities

While designing OGSPs with optimal fault tolerant manipulability, it is important to identify symmetric OGSPs which may be rendered singular under the occurrence of one fault. At the onset of singularity, unexpected motions are possible and the manipulator cannot be controlled. This is highly undesirable and potentially destructive. The following Theorem develops the necessary and sufficient condition to identify optimal fault tolerant OGSPs with potential singularity problems.

Theorem 7. Let M be the inverse Jacobian matrix of an OGSP with two groups. Then, ${}_iM^T M$ is singular if and only if the group in which failure occurs has at most 3 struts.

The following lemma is necessary to prove the Theorem.

Lemma 8. For any $m \times n$ matrix, M ,

$$\text{rank}(M^T M) = \text{rank}(M). \quad (44)$$

Proof of lemma: Clearly,

$$\text{rank}(M^T M) \leq \text{rank}(M). \quad (45)$$

Let $M^T Mx = 0$ for $x \in \mathbb{R}^n$.

Then,

$$\langle M^T Mx, x \rangle = \langle Mx, Mx \rangle = \|Mx\|^2 = 0. \quad (46)$$

Hence, $Mx = 0$.

#

Proof of Theorem: Suppose that ${}_iM^T M$ is singular. Then,

$$\text{rank}({}_iM^T M) \leq 5.$$

Proposition 7 in (Aphale, 2006) determines the rank of M for an OGSP, having p groups of struts:

$$\text{rank}(M) = \min(\sum_1^p \text{rank}(M_p), 6) \quad (47)$$

where M_p denotes the inverse Jacobian matrix of the p^{th} group.

In the context of failures, this proposition directly implies

$$\text{rank}_i(M) = \min(\sum_1^p \text{rank}_f^p(M), 6) \quad (48)$$

where $^p M$ denotes the inverse Jacobian matrix of the p^{th} group having f strut failures within the group. That is, $\sum f = i$.

Applying Lemma 8 to equation (48), we have

$$\text{rank}_i(M^T M) = \min(\sum_1^p \text{rank}_f^p(M^T M), 6). \quad (49)$$

The nominal OGSP under consideration consists of two groups of struts. Hence,

$$\text{rank}_i(M^T M) = \min[\sum_{e=1}^2 \text{rank}_{f_e}^e(M^T M), 6] \quad (50)$$

where $f_1 + f_2 = i$. Theorem 1 in (Aphale, 2006) establishes that the maximum rank of the Jacobian matrix of a group of struts forming an OGSP is 3. Therefore, $M^T M$ is singular if the group in which any failure occurs has at most 3 struts. The converse is immediate.

#

Remark: It is worthwhile to note that unitarily equivalent Jacobian matrices (and inverse Jacobian matrices) have the same manipulability, and it may be readily checked that all single failure reduced inverse Jacobian matrices of a 2s OGSP with an [s s] geometry generated by Theorem 4 are unitarily equivalent. This observation highlights the fact that these designs produce manipulators with optimal fault tolerant manipulability.

5.3 Application example: air borne laser (ABL)

Currently, feasibility of missile defense using an aircraft equipped with a high energy laser is being explored. At the concept level, the system uses a mirror inside the fuselage which focusses a beam from a megawatt-class chemical laser. Optic and beam control systems keeps the beam locked on a small supersonic target hundreds of kilometers away. It is believed that ABL can destroy hostile theater ballistic missiles while they are still in the highly vulnerable boost phase of flight before separation of the warheads. ABL can operate above the clouds, where it is possible to autonomously detect and track missiles as they are launched, using an onboard surveillance system. The defense system acquires the target, then accurately points and fires the laser with sufficient energy to destroy the missile. Airborne optical or electro-optical systems may be too large for all elements to be mounted on a single integrating structure, other than the aircraft fuselage itself. An eight-legged six-DOF OGSP (Octopod) is a perfect candidate to maintain the required alignment between

elements. However the various smaller integrating structures (benches) must still be isolated from high-frequency airframe disturbances that could excite resonances outside the bandwidth of the alignment control system. The combined active alignment and vibration isolation functions must be performed by flight-weight components, which may have to operate in a vacuum. The platform used must be able to perform the dual functions of low-frequency alignment and high-frequency isolation (Keinholz, 1999).

The manipulability requirements for OGSPs intended for such an application are very demanding and Aphale (Aphale, 2006) describes them in detail. It is also shown (Aphale, 2005) that OGSPs are capable of meeting the manipulability requirements, making them suitable for the ABL application. Failure tolerance is imperative for this missile defense application. Furthermore, it is difficult to predict specific failures at the design stage and as such failure of any actuator is considered equally likely. If an equal reduction of manipulability is desired under a failure of any strut, an OGSP with optimal fault tolerant manipulability is an excellent choice.

6. Conclusions and future work

6.1 Conclusions

This work proves that for a certain class of parallel manipulators functioning about a single point in its workspace, the mean squared relative manipulability over all possible cases of a given number of actuator failures is always constant irrespective of the geometry of the manipulator. In this context, optimal fault tolerant manipulability is defined and quantified using a simple algebraic formulation. The definition is more suited to parallel manipulators since they can retain kinematic stability under failures which constitute loss of actuators.

For micromanipulation, symmetric OGSPs can be designed to possess optimal manipulability under actuator failures. OGSP geometries that may be rendered singular due to faults can be identified and avoided. OGSPs with optimal fault tolerant manipulability are highly suitable for critical applications since they retain a reasonable and equal fault tolerant performance if any actuator fails. For example, Figure 3 illustrates a cylindrical [4 4] OGSP that can be used in aerospace applications with ABL. These OGSPs will provide operational reliability critical to the application.

6.2 Future work

Currently most OGSPs are seen to have a very small range of motion in the joint space. In such scenarios, the assumption that the Jacobian matrix remains constant with respect to time, is valid. Recent applications demand OGSPs with a larger range of motion. The assumption of the Jacobian being constant does not hold validity in such cases. Investigating the fault tolerant characteristics of a manipulator Jacobian which will take into account the change with respect to time can be of great practical importance. It has recently been shown (Roberts, Yu & Maciejewski, 2007) that, regardless of a manipulator's geometry or the amount of kinematic redundancy present in a manipulator, no fully spatial manipulator Jacobian can be equally fault tolerant to three or more joint failures. Due to these constraints in generalization, it would be useful to formulate manipulator Jacobian matrices that possess equal fault tolerance to specified scenarios involving multiple failures. In particular, weights can be assigned to relative manipulability indices corresponding to multiple failure

scenarios and optimized values of relative manipulability can be obtained based on the result derived in Theorem 1. Exploring the application of design and control techniques devised for OGSPs in areas of medical robotics and haptic interfaces can be considered. Robotics holds promise in standardized surgical procedures like eye surgery, knee surgery, etc. The theory developed thus far can be applied efficiently in medical applications where principles of robotics and computer vision combine towards a single objective. Multiple finger grasp mechanisms and other parallel manipulators have been considered for such applications. In these applications there is a need to withstand failures with almost no degradation in performance. It is possible to transfer many theories and techniques related to parallel manipulators to the analysis of multiple finger grasps with some modification.

It would be worthwhile to consider optimizing control for grasps such that fault tolerance can be achieved. Internal force calculations have been done for parallel mechanisms like multi-finger grasp mechanisms (Kerr & Roth, 1986). Internal force issues in other forms of parallel manipulators have also been explored (Lebret, Liu & Lewis, 1993) (Hiller and Schneider, 1997). Literature on the internal forces generated in GSPs is limited. OGSPs being a very recently defined class haven't been explored with respect to the internal forces they generate and need to withstand. With redundancy comes more number of actuators than the required minimum and a large number of constraints associated with them. Under failures, internal forces will be a major factor in the dynamics and control of OGSPs. Generating OGSPs that provide equal tolerance to failures with respect to the dynamic manipulability index seems feasible.

Finally, it is most important to recognize that the main contribution of this work is a combinatorial result in linear algebra. Numerous systems in various disciplines can be modeled by matrices. For instance, matrices are used to model power transmission and distribution systems. In matrix models where failures amount to elimination of rows and (or) columns, the theory of fault tolerance developed thus far would be useful and worthwhile extending.

7. References

- Aphale, S. (2006). *Designing orthogonal gough-stewart platforms with robust fault tolerance*, ProQuest / UMI, ISBN-10: 0542313596, Ph.D. Dissertation, University of Wyoming, Laramie, WY.
- Baillieul, J. (1996). Avoiding obstacles and resolving redundancy, *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 1698 – 1703, San Francisco, CA., April 1990.
- Hiller, M. & Schneider, M. (1997). Modeling, simulation and control of flexible manipulators, *European Journal of Mechanics*, vol. 16, 1997, page numbers 127-150.
- Hollerbach, J. M. & Suh, K. C. (1987). Redundancy resolution of manipulators through torque optimization, *IEEE Journal of Robotics and Automation*, vol. RA-3, no. 4, August 1987, page numbers 308-316.
- Kerr, J. & Roth, B. (1986). Analysis of multifingered hands, *International Journal of Robotic Research*, vol. 4, no. 4, 1986, page numbers 3-17.

- Kim H. W. ; Lee J. H. ; Yi, B. J & Suh I. H. (2004). Singularity-free load distribution algorithms for a 6 dof parallel haptic device, *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 298-304, New Orleans, LA., May 2004.
- Kock, S. & Schumacher W. (1998). A parallel x-y manipulator with actuation redundancy for high speed and active stiffness applications, *Proceedings of IEEE International Conference on Robotics and Automation*, , pp. 2295-2300, Leuven, Belgium, May 1998.
- Lebret, G.; Liu, K. & Lewis, F. L. Dynamic analysis and control of a stewart platform manipulator, *Journal of Robotic Systems*, vol. 10, no. 5, 1993, page numbers 629-655.
- Lewis, C. L. & Maciejewski, A. A. (1992). Dexterity optimization of kinematically redundant manipulators in presence of faults, *Proceedings of Fourth International Symposium on Robotics and Manufacturing*, pp. 279-284, Santa Fe, NM., November 1992.
- Maciejewski, A. A. (1990). Fault tolerant properties of kinematically redundant manipulators, *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 638-642, Cincinnati, OH., May 1990.
- McInroy, J. E. ; O'Brien, J. F. & Neat, G. W. (1999). Precise, fault-tolerant pointing using a stewart platform, *IEEE/ASME Transactions on Mechatronics*, vol. 4, no. 1, March 1999, page numbers 91-95.
- McInroy, J. E. & Jafari, F. (2006). Finding symmetric orthogonal gough-stewart platforms, *IEEE Transactions on Robotics and Automation*, vol. 22, no. 5, October 2006, page numbers 880-889.
- Paredis, C. J. J. ; Au, W. K. F. & Khosla, P. K. (1994). Kinematic design of fault tolerant manipulators, *Computers Electrical Engg.*, vol. 20, no. 3, 1994, page numbers 211-220.
- Roberts, R. G. & Maciejewski, A. A. (1996). A local measure of fault tolerance for kinematically redundant manipulators, *IEEE Transactions on Robotics and Automation*, vol. 12, no. 4, August 1996, page numbers 543-552.
- Roberts, R. G.; Yu, H. G. & Maciejewski, A. A. (2007). Characterizing Optimally Fault-Tolerant Manipulators Based on Relative Manipulability Indices, *2007 International Conference on Intelligent Robots and Systems (IROS 2007)*, pp. 3925-3930, San Diego, CA., Oct. 29 - Nov. 2, 2007.
- Stewart, D. (1966). A platform with six degrees of freedom, *Proceedings of Institution of Mechanical Engineers*, Part 1, vol. 180, no. 15, 1966, page numbers 371-378.
- Ting, Y. ; Tosunoglu, S. & Tesar, D. (1993). A control structure for fault-tolerant operation of robotic manipulators, *Proceedings of IEEE International Conference on Robotics and Automation*, , pp. 684-690, Atlanta, GA., May 1993.
- Ukidve, C. S. ; McInroy, J. E. & Jafari, F. (2006). Orthogonal Gough-Stewart Platforms with optimal fault tolerant manipulability, *Proceedings of IEEE International Conference on Robotics and Automation*, pp. 3801-3806, Orlando, FL., May 2006.
- Wapler, M. ; Urban, V.; Weisener, T.; Stallkamp, J. ; Durr, M. & Hiller, A. (2003). A stewart platform for precision surgery, *Transactions of the Institute of Measurement and Control*, vol. 25, no. 4, 2003, page numbers 329-334.

- Wen, J. T.-Y. & Wilfinger, L. S. (1999). Kinematic manipulability of general constrained rigid multibody systems, *IEEE Transactions on Robotics and Automation*, vol. 15, no. 3, June 1999, page numbers 558-567.
- Yoshikawa, T. (1985). Manipulability of robotic mechanisms, *International Journal of Robotics Research*, vol. 4, no. 2, 1985, page numbers 3-9.

IntechOpen

IntechOpen



Parallel Manipulators, towards New Applications

Edited by Huapeng Wu

ISBN 978-3-902613-40-0

Hard cover, 506 pages

Publisher I-Tech Education and Publishing

Published online 01, April, 2008

Published in print edition April, 2008

In recent years, parallel kinematics mechanisms have attracted a lot of attention from the academic and industrial communities due to potential applications not only as robot manipulators but also as machine tools. Generally, the criteria used to compare the performance of traditional serial robots and parallel robots are the workspace, the ratio between the payload and the robot mass, accuracy, and dynamic behaviour. In addition to the reduced coupling effect between joints, parallel robots bring the benefits of much higher payload-robot mass ratios, superior accuracy and greater stiffness; qualities which lead to better dynamic performance. The main drawback with parallel robots is the relatively small workspace. A great deal of research on parallel robots has been carried out worldwide, and a large number of parallel mechanism systems have been built for various applications, such as remote handling, machine tools, medical robots, simulators, micro-robots, and humanoid robots. This book opens a window to exceptional research and development work on parallel mechanisms contributed by authors from around the world. Through this window the reader can get a good view of current parallel robot research and applications.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Chinmay S. Ukidve, John E. McInroy and Farhad Jafari (2008). Quantifying and Optimizing Failure Tolerance of a Class of Parallel Manipulators, *Parallel Manipulators, towards New Applications*, Huapeng Wu (Ed.), ISBN: 978-3-902613-40-0, InTech, Available from:

http://www.intechopen.com/books/parallel_manipulators_towards_new_applications/quantifying_and_optimizing_failure_tolerance_of_a_class_of_parallel_manipulators

INTECH
open science | open minds

InTech Europe

University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2008 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the [Creative Commons Attribution-NonCommercial-ShareAlike-3.0 License](https://creativecommons.org/licenses/by-nc-sa/3.0/), which permits use, distribution and reproduction for non-commercial purposes, provided the original is properly cited and derivative works building on this content are distributed under the same license.

IntechOpen

IntechOpen